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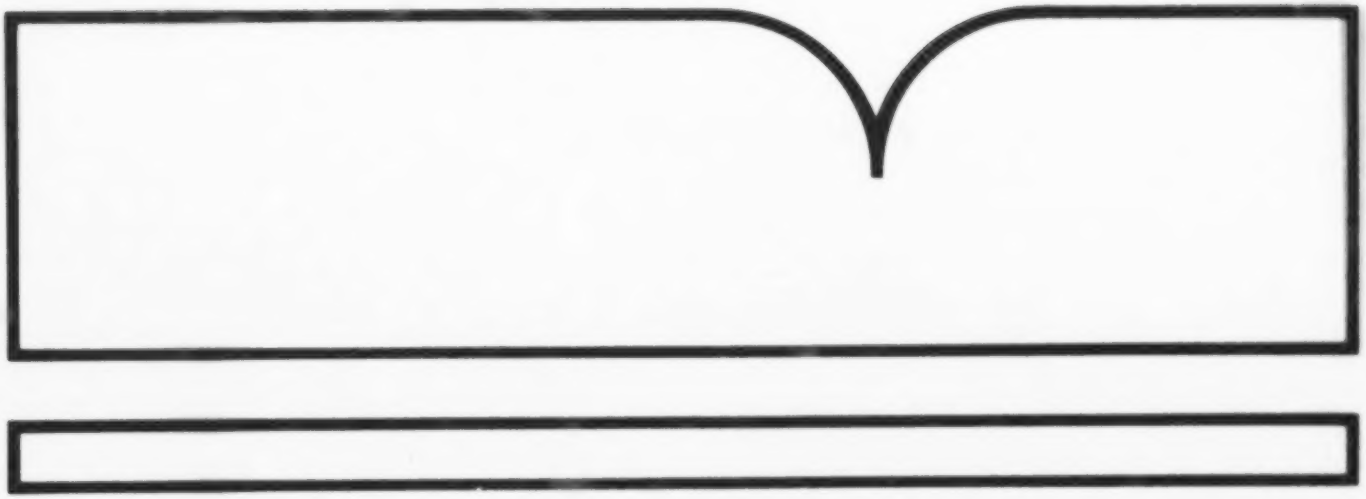

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16. ABSTRACT

This paper presents al review of public safety standards as adapted by the nuclear weapons testing program in the United States, and the impact of these changing standards on the nuclear testing program itself. The review notes the importance of improvements in diagnostic instrumentation and methodologies from a relatively simple degree of sophistication to their current high level. Use of the improved methodologies uncovered a serious oversight affecting human exposure, namely, that of not recognizing the relative importance of all potential transport/dosimetric pathways for risk assessment.

The testing program, from its inception in the Pacific in 1946 to the present time in Nevada, is viewed from the perspective of providing improved radiation protection to the general public.

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REVIEW ARTICLE

# HISTORICAL PERSPECTIVES ON SELECTED HEALTH AND SAFETY ASPECTS OF NUCLEAR WEAPONS TESTING*

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**Abstract**—This paper presents a general review of public safety standards as adapted by the nuclear weapons testing program in the United States, and the impact of these changing standards on the nuclear testing program itself. The review notes the importance of improvements in diagnostic instrumentation and methodologies from a relatively simple degree of sophistication to their current high level. Use of the improved methodologies uncovered a serious oversight affecting human exposure, namely, that of not recognizing the relative importance of all potential transport/dosimetric pathways for risk assessment.

The testing program, from its inception in the Pacific in 1946 to the present time in Nevada, is viewed from the perspective of providing improved radiation protection to the general public.

## I. INTRODUCTION

FOR THOSE working in the field of operational health physics, it is of interest to understand the influence of regulations pertaining to radiation safety on the nuclear weapons testing procedure and how these regulations have changed during the past 40 yr.

After the Trinity test in 1945, the early nuclear testing programs were conducted in the Pacific Proving Grounds at Bikini Atoll in 1946 and Enewetak Atoll in 1948. In 1950, the U.S. Government decided to establish a continental proving ground as a facility for testing nuclear weapons because it was desirable to avoid interference in shipping lanes or air corridors, to provide additional security, and for economic reasons. This facility, now known as the Nevada Test Site (NTS), was established from a portion of the Nellis Air Force Bombing and Gunnery Range and was to be used to conduct atmospheric tests, with the proviso that the population living around the site should be protected from the effects of the planned nuclear tests.

Risks to the public from nuclear explosions arise from the phenomena associated with air- or ground-borne acoustic shock waves, the fireball thermal output, the optical flash, and ionizing radiation. Ionizing radiation can lead to public exposure from internal as well as external routes. External exposure could occur from the prompt radiations during the explosion, from radioactivity in the debris cloud during its passage, and from ground-deposited debris after cloud passage. Internal exposure could result from inhalation of radioactive materials during cloud passage, from resuspension of previously deposited material, from the ingestion of radioactive materials deposited on foodstuffs as well as those transported through the food chain. The food-chain relationships for most radioisotopes were poorly defined in the 1950s, however, the effects of resuspension and rainout were recognized.

Some effects of nuclear weapons tests—shock, heat, flash and prompt $\gamma$ radiation—are mini-

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mized by conducting such tests far from populated places, and by restricting air space around the NTS which precludes potential hazard to commercial aircraft.

Furthermore, the amount of radiation exposure to which the off-site population (people living in areas surrounding the NTS) is subjected because of radioactive debris transported through the atmosphere (the fallout cloud) can be minimized by careful selection of the weather conditions at the time of the test. For example, the wind direction can be selected so no large population would be encountered until the fallout cloud is widely dispersed, and so no precipitation (rainout) would occur during cloud passage in the off-site area until many hours after the test (AEC53c). In the event of unfavorable weather conditions a test can be postponed. An expert committee reviews all available atmospheric data before each test.

Since 1964 the policy adopted for weapons tests requires that testing be conducted underground in addition to observing the above conditions. In the 20 yr since that policy was adopted, only three major accidental releases have occurred (Pike, Pin Stripe, Baneberry). However, during the 1960s several Peaceful Nuclear Explosive (cratering) experiments were conducted which also released radioactivity detectable off the NTS, i.e. Sedan, Cabriolet, and Schooner.

External radiation exposure limits for radiation workers and the general population were set by the U.S. Atomic Energy Commission (AEC) using criteria published by recognized authorities but suitably modified, with appropriate conservative factors as discussed below, to meet local conditions. For internal exposure, at least during the early years of nuclear testing, there was a paucity of information on which to base public radiation standards, and few procedures were established for calculating the internal dose resulting from either inhalation or ingestion of radioactive materials. The measurements and estimates prepared were primitive relative to our current capabilities.

A brief history of the development of internal exposure standards, of recognized hazards, of dosimetry, of bioassay (particularly for radioiodine), and of NTS exposure standards is presented in the following sections. Each section is arranged chronologically. The biological aspects of internal emitters have recently been reviewed (Bo83) and are not repeated herein. In many cases the original references were not available so the accuracy of the related materials is subject to the bias, if any, of the authors citing the original work.

To place the events in this review into a temporal context, it is of interest to note that the year 1984 marked the fiftieth anniversary of the production of artificially radioactive species by Joliot and Curie (Jo34).

## II. INTERNAL EXPOSURE STANDARDS

The hazard due to external radiation exposure was recognized soon after the discovery of x rays by Roentgen in 1895, and standards for such exposure were established in the early 1920s. The hazard due to internal exposure to radioactive materials surfaced later in the 1920s. The impetus for development of standards for internal exposure was the identification of harmful effects in an occupational group now called the Ra dial painters. As a result of extensive studies on these workers, and others who had accumulated Ra body burdens accidentally or from medical treatments, the Advisory Committee on X-ray and Radium Protection in 1941 published a standard for the maximum permissible body burden (MPBB) of $^{226}$Ra, namely, 0.1 $\mu$g (ACX41). This quantity was the basis upon which standards for other internally deposited radioisotopes were founded, generally by comparing or estimating the effects produced relative to those produced by $^{226}$Ra. The radium MPBB was re-evaluated in 1967 and still found to be valid (Ev67). After a hiatus during World War II, promulgation of standards for internally deposited radionuclides was resumed by national and international committees.

In 1951, the International Commission on Radiological Protection (ICRP) published data on the maximum permissible exposure to $^{3}$H, $^{14}$C, $^{24}$Na, $^{32}$P, $^{60}$Co, $^{89}$Sr, $^{90}$Sr, $^{131}$I, $^{210}$Po, $^{226}$Ra, and $^{239}$Pu (ICRP51). These standards were applied to occupational workers by agencies in the United States, the United Kingdom and Canada. Maximum permissible concentrations (MPCs) for these radionuclides in air and liquids were included.

Standards for MPCs in air and water for $^{137}$Cs and about 57 other radionuclides were added in 1953 (NCRP53). These and the other radionu-

clides were considered more hazardous when inside the body than when outside because they: (1) irradiate continuously, (2) have a long biological half-life, (3) are difficult to remove, (4) are in intimate contact with sensitive tissues or are incorporated into cells, and (5) because most of the energy dissipated during radioactive decay is absorbed in the tissues within which they reside. The difficulties encountered at that time in locating, identifying and quantifying internally distributed radionuclides added to the uncertainties of defining radiation doses. *National Bureau of Standards* (NBS) *Handbook* 52 (NCRP53) further recommended a value of 1 nCi $m^{-3}$ (37 Bq $m^{-3}$) of air and 0.1 nCi $L^{-1}$ (3.7 Bq $L^{-1}$) of water for unknown mixtures of $\beta$ or $\gamma$ emitters beyond those areas under control of the responsible installation.

Standards published in *NBS Handbook* 59 (NCRP58) and *NBS Handbook* 69 (NCRP59) set MPCs in air or water for more than three times as many isotopes as had been considered previously. In the succeeding years, few substantial changes have been made to the 1959 recommendations. Those few have been due to special circumstances or conditions as outlined by the Federal Radiation Council (FRC). For example, in 1961 the FRC recognized that although the fractional uptake of a dose of radioiodine by the thyroid was the same in both adults and children, the small size of the child's thyroid gland resulted in a much greater (up to tenfold) concentration (FRC61). Therefore, the FRC recommended that $^{131}I$ in milk not exceed 100 pCi $L^{-1}$ (3.7 Bq $L^{-1}$) when averaged over a year. In 1964 the FRC recommended that the dose to the thyroid of an individual from a single contaminating event not exceed 30 rad (0.3 Gy) without protective action, and that the calculated average dose should not exceed 10 rad (0.1 Gy) to a 2-g thyroid (FRC64). This 0.1-Gy dose is predicted to occur when the peak concentration in milk from a single event reaches 60–70 nCi $L^{-1}$ (2.22 to 2.59 kBq $L^{-1}$), when no action is taken to prevent further intake, and when certain metabolic assumptions are made. A later significant change was recommended in 1977 and 1979 by the ICRP, when weighting factors and the concept of effective dose equivalent were introduced (ICRP77; ICRP79).

During the period from 1933 to the present, the external radiation exposure guide has been reduced from 1 rem per week ($10^{-2}$ Sv per week) to one-tenth of that value (ACX34). Also, the MPCs in air and water, established in 1949, have been lowered correspondingly. However, these changes did not result from any *positive* evidence of damage associated with exposures at the earlier permissible dose levels (MPDs) but, as stated in the addendum to *NBS Handbook* 59 (NCRP58), were based on the desire to bring the MPD into accord with trends of scientific opinion.

## III. RECOGNIZED HAZARD

All the previously mentioned standards were based on continuous exposure of workers to radionuclides for long periods of time (usually 50 yr) from the operation of medical, radiochemical or processing facilities. It was unclear how to apply such guidelines to nuclear weapons tests where exposures, if any, were brief and highly intermittent. Nevertheless, guidelines for such tests were designed so that any radiation exposures would be minimal. These guidelines were based on the recognized hazards described next.

During the early period of nuclear weapons testing, external radiation exposure was considered more hazardous than internal exposure when both were caused by local fallout, i.e. fallout within a few hundred miles of a nuclear test. This was affirmed many times by advisory groups and published data. The following statements, selected from the published literature, are paraphrased to illustrate this point:

(a) In 1950 (Co50): If in a given area the dosage due to external radiation is down to a safe level, there will, in general, be little, if any, danger of enough radioactive material being fixed in the system for it to constitute an internal hazard.

(b) For Marshall Islanders exposed in 1954 (Co80): Internal dosimetry was based on analysis of urine collected 15 days post-exposure, the sum of the radionuclides indicated approximately 0.4 of the maximum permissible body burden was reached while the external exposure of 175 rad (1.75 Gy) was many times the standard. The early calculation for thyroid dose was 100–150 rad (1.0–1.5 Gy). This dose was recalculated in 1964 (Ja64b); the sum of external plus internal dose to the thyroid was estimated as 335 rad (3.35 Gy) for adults but 700–1400 rad (7–14 Gy) for children. In 1980, the dose to the thyroid of a child

was again revised upward to 810–1800 rad (8–18 Gy) (Co80).

For 23 Japanese fishermen, the thyroid dose range, 80–450 rad (0.8–4.5 Gy), was less than the external exposure range of 170–600 rad (1.7–6.0 Gy).

(c) For rabbits exposed to fallout by inhalation and external exposure, at 7 and 106 miles (11 and 171 km) from a test in 1955 (Ta58): At the 7-mile (11-km) station, urine collected the first day contained small amounts of activity with a one- to two-day half-life. The internal dose could be expressed in millirem (nSv) while the external exposure was 14–32 R (3.6–8.2 mC $kg^{-1}$). At 106 miles (171 km) there was no measurable activity in lung or urine, and the external exposure approached 4 R (1 mC $kg^{-1}$).

(d) From a National Academy of Sciences-National Research Council report in 1956 (NAS56): With reference to fallout from nuclear detonations, consideration of physical factors and actual experience indicates that the acute external $\beta$-$\gamma$ radiation hazard is many times greater than that from inhalation. The only situation worth considering in relation to large-scale pathological effects would be widespread contamination with $^{90}Sr$.

(e) In congressional hearings in 1959 (St59): All data show that the dose to the thyroid from I isotopes will be the largest single internal dose, the gastrointestinal tract second, and the respiratory tract and skeleton third. In all cases, the total internal doses will be small compared to the external radiation dose.

(f) The National Council on Radiation Protection and Measurements stated in 1961 (NCRP62): (1) Most available evidence indicates that radioactive material taken into the body immediately after a nuclear attack will be less important than whole-body exposure to $\gamma$ radiation, and (2) the water supply is generally considered an important source of internal hazard for the whole population due to fallout while for domestic animals the food supply may be more important.

(g) In the book *The Effects of Nuclear Weapons* (Gl62): "There seems to be little doubt, therefore, that, at least as far as short-term effects are concerned, the radiation injury by early fallout due to internal sources can be quite minor in comparison with that due to external radiation."

Acknowledging that these were the opinions of recognized experts and skilled experimental scientists, the U.S. AEC's Division of Biology and Medicine, following their advice, was more concerned about external radiation exposure than about internal. The exposure standards they set, then, assumed that if the external exposure was maintained at or below the permissible level, then the internal exposure for the same people at risk would also be within any standards.

However, the possibility of exposure from internally deposited radionuclides had not been ignored. Because of the fallout experience at the Trinity site and other areas, theoretical studies on the hazards of fallout had been instituted by the AEC in the 1940s under the name Project Gabriel. In 1949, based on its long half-life and its possible retention in the body as an analog of Ca, $^{90}Sr$ was considered to be the most hazardous fission product (Sm54). This was under intensive study at many laboratories, and remained the prime candidate for biological concern until the early 1960s. Monitoring for this element in milk and human bone is a continuing activity at many places (La85).

Cesium was also an early candidate for the most hazardous fission product because of its long half-life and its metabolic pattern, resembling K. Because Cs does not concentrate in particular organs and because it has a relatively short biological half-life, the committed dose equivalent was expected to be much less than that from $^{90}Sr$. Also, there is discrimination by plant uptake against Cs so that at early times after fallout the principal ingestion pathway is via milk. These factors abated serious concern about the health hazards from $^{137}Cs$ in fallout, but Cs continued to be reported because it was readily detectable and because it could be used to estimate the presence of $^{90}Sr$ (An57).

In general, many of the above statements are still pertinent, however, concern was redirected from Cs and Sr to radioiodine when measurements of this radionuclide in milk samples collected from areas in northeastern Utah in 1962 and reported in 1963 (Ma63) indicated that the calculated dose to an infant's thyroid from the continuous consumption of such milk could be substantial. For example, the dose was 10 rem (0.1 Gy) when the peak milk concentration was 60–70 nCi $L^{-1}$ (2–3 kBq $L^{-1}$) (FRC64). The relatively rapid forage-cow-milk chain for radioio-

dine transport and the calculated dose to an infant's 2-g thyroid (10 times that to an adult's 20-g thyroid) had been relatively neglected factors for use in internal dose computations before that time. In Dunning's classic paper (Du56) on estimating thyroid dose from radioiodine in fallout, that dose is calculated using only the inhalation pathway.

Of course, there had been studies related to radioiodine that had suggested little hazard from this element and some of these will be described.

For the Upshot-Knothole test series in 1953, the solubility of fallout particles in 0.1 N HCl (simulating gastric acidity) was reported as only 2% (Ra54). Beta-emitter concentrations measured in milk from Nevada and Utah, when compared to tolerance values for water, did not constitute an internal hazard (Jo53), and studies on rodents in Nevada indicated that since ingestion was the major route for uptake of radioactive materials (Li54) at locations near a test, time was available for radioactive decay while the radionuclides traversed the food chain, thereby reducing exposure. Unfortunately, many workers at that time did not realize that a large fraction of the radioiodines would be vaporized upon acid dissolution, the sample preparation procedure then commonly in use.

For distant locations, inhalation was suggested as the major route for radioiodine intake. In California, in the summer of 1954, measurements were made of $^{131}I$ in feed and in thyroids of cattle, sheep, a horse, pig, and dog. The similarity of radioiodine burdens in thyroids, despite different food habits, implicated inhalation exposure (Gu54). Studies on fallout at closer distances during the Teapot test series suggested inhalation was a negligible route (Li59). Here $^{90}Sr$ was used as the indicator for uptake by rabbits and small rodents whose ingestion was restricted. These findings could be assumed to apply to the other fission products as well.

Other studies on this subject, directly related to radioiodine, also indicated little hazard from this element. During the Teapot test series in 1955, 24-hour urine collections were taken from 10 volunteers at each of 17 locations in the United States including U.S. Public Health Service (PHS) monitors stationed near the NTS. These were analyzed for $^{90}Sr$ and $^{131}I$ by use of radiochemical methods. The average concentration of $^{131}I$ in 24-hr urine samples during the 91-day test period varied by a factor of 10 between a high at Ogden, UT, to a low at San Francisco, CA (Sc58). The maximum excreted was about 220 pCi per 24 hr (8 Bq per 24 hr). At the same time, gross $\gamma$ measurements were made over the thyroid glands of 20 PHS personnel and family members stationed in Nevada and Utah. Except for two cases with an estimated thyroid burden of 5 nCi (185 Bq) of $^{131}I$, all measurements indicated less than the detectable amount of 2 nCi (74 Bq) (Va56).

Two studies compared animal with human thyroid burdens. From January 1955 to October 1956, measurements were made of $^{131}I$ in 853 cattle thyroids and 1,165 human thyroids. The total dose to the bovine thyroid was approximately 4 rad (0.04 Gy) over that 21-month span, but only 0.013 rad (0.13 mGy) to the human thyroid (Tr58; Co57). In similar studies (Wh56; Wh58), it was reported that beef thyroids had 460 times as much $^{131}I$ from NTS tests as did human thyroids. From these and other studies many experts felt that fallout radioiodines were not a problem and were not likely to become a problem in the future (Jo57; St57). The report of the Sub-committee on Toxicity of Internal Emitters, National Academy of Sciences-National Research Council, in the 1957 hearings before the Joint Committee on Atomic Energy (Br57) states, "In view of the short half-life of $^{131}I$, it can be concluded that the hazard of bomb tests from this standpoint is negligible."

All these studies suggested that radioiodine intake by inhalation was important only at distant locations, that intake via ingestion was much greater than from inhalation at near locations, and that the thyroid burden of domestic animals was many times higher than that of humans from the same area. None of the measurements indicated that radioiodine should be a cause for concern. This was stated by Comar (Co57): "There seems to be little question that the levels of radioiodine introduced into the biological cycles by weapons tests during 1955 and 1956 are far below those that are expected to produce any observable effects." Further evidence for the lack of concern over the fallout radioiodines is shown throughout the 1959 congressional hearings on fallout from nuclear weapons tests (Jo59).

In 1959, E. B. Lewis (Le59) reviewed the data for humans up to the end of September 1958, and concluded that, "The thyroid glands of average infants and children in the U.S. are esti-

mated to have experienced over the last few years annual doses of about 0.1–0.2 rad [1–2 mGy] from the radioiodine in fallout." The following year, *FRC Report No. 2* (FRC60) recommended that a dose of 0.5 rem (5 mSv) delivered over 1 yr to children's thyroids should not be exceeded. This report did not provide any indication of the potential hazard from the transport and metabolism of other radioactive iodines.

The findings following the reactor accident at Windscale, England, in October 1957 (Bo58) appeared to contradict the interpretation of the preceding experimental data. However, the Windscale release was primarily gaseous and about 50% of the radioactivity was due to $^{131}I$ (Be61) as compared to about 3% (fission yield) in a nuclear explosion (Ho63). Although milk collected within a few miles of the reactor had estimated $^{131}I$ concentrations of 1 $\mu$Ci $L^{-1}$ (37 kBq $L^{-1}$), the concentration decreased rapidly with distance so that milk collected 60 miles (100 km) from Windscale had concentrations of less than 50 nCi $L^{-1}$ (1.85 kBq $L^{-1}$). Considering the disparities of radioiodine percentages, the distances from the NTS to any commercial dairy herds, the results of the experiments discussed above and intermittent nature of these exposures, it is easy to speculate that the AEC assumed that radioiodines in fallout from NTS tests would not cause significant exposure to the off-site population. In fact, in the three volumes of the 1959 congressional hearings (Jo59), radioiodine was rarely discussed: the emphasis was still on $^{90}Sr$ and $^{137}Cs$.

It was well known that iodide and radioiodines concentrate in the thyroid gland, and the metabolism of I had probably been more intensely studied and documented than almost any other trace element (Ch55; Br63). Yet, indications of an adverse effect from relatively low doses were not reported until studies by Hempleman (He68) showed epidemiologically that children treated for enlarged thymus by x irradiation later exhibited a significantly higher rate of thyroid carcinoma and that the dose-response curve was probably linear, at least from 20–1200 rad (0.2–1.2 Gy).

Pertinent to the foregoing and other hazards from fallout intake was a study conducted in 1962 and reported in 1964 (Le64); only about 3% of the radioactivity contained in an orally administered dose of week-old fallout, collected 4500 feet (1400 m) from a test at the NTS, was absorbed by healthy volunteers (range 0 to 9%). This was about one-third the amount absorbed that had been previously assumed. Calculations by the authors of that report suggested that ingestion of one-day-old fallout containing 5 mCi (1.85 GBq) of mixed fission products would deliver about 100 rad (1 Gy) to the lower large intestine. They assumed that doses greater than about 100 rad (1 Gy) could cause diarrhea and decrease further absorption of material (*NAS-NRC Publication No. 1487*, page 248, indicates a 10% probability of diarrhea at 90 rad [0.9 Gy]).

In about 1962 several separate facts, each of which were known much earlier, were to come together to make radioiodine the specific concern of the 1960s as radiocesium and radiostrontium were for the 1950s. These were: (1) radioiodine concentrates in the thyroid gland, (2) this radioiodine concentration in the thyroid is a percentage of administered (ingested) dose regardless of the size of the gland, (3) the infant's thyroid weighs approximately one-tenth to one-twentieth that of the adult, (4) dairy cows grazing on contaminated pasture act as a collector of radioiodine by grazing over many square meters of forage per day, depending on the density of forage, (5) a measurable fraction of the radioiodine ingested by the cow is transferred to its milk which is ingested by humans, and (6) the time frame for the transport of radioiodines from deposition of nuclear debris to humans via the forage-cow-milk food chain is relatively very rapid, usually a matter of a few days and sometimes less as in the case of the rural single-cow family. Thus, the radiation dose delivered to the thyroid gland of an infant consuming 1 L of such contaminated milk per day for an extended period could be more than an order of magnitude greater than for adults consuming the same amount of contaminated milk. In addition, it has been assumed that growing tissues, such as those in a child, are much more sensitive to irradiation than those of an adult, thus increasing the potential hazard (FRC64).

The first real public attention to the radioiodine problem surfaced in the 1962 congressional hearings (Jo62) which included reports on the measurement of radioiodines in milk and in human thyroid glands in the United States. This was attributed to fallout from the Soviet weapons testing program which had resumed in 1961. In

this same year an FRC report included the following: "Radioactive iodine has been shown to be carcinogenic in animals but no case of thyroid cancer ascribable to it has been found in man" (FRC62). However, by the time the 1963 hearings on Fallout Radiation Standards, and Countermeasures were held, radioiodine had become a nuclide of principal concern. This publication contained presentations by Mays (Ma63) and Knapp (Kn63) which had considerable impact on the public as well as on the scientific community as evidenced by the number of radioiodine studies that were instituted. An extensive sample of these is included in the December 1963 issue of *Health Physics* (Pr63).

As a result of the 1962 radioiodine exposure calculations in Utah (Ma63), mentioned previously, all known pathways leading to internal exposure have been considered (see, for example, Ng *et al.* (Ng68) and subsequent reports by these authors) so that internal exposures based on ICRP and NCRP guides (NCRP59) would not be exceeded. If there are other critical combinations such as those revealed by the 1962 radioiodine incident, they have not been reported despite these intensive investigations.

Concern about ingestion and/or inhalation of fission products from weapons tests was decreased after the Limited Test Ban Treaty was signed in August 1963. This treaty banned the testing of nuclear weapons in the atmosphere but permitted underground tests. Thereafter, except for accidents, fission products from the tests would be retained at the test sites. For cratering tests under the Plowshare Program* the explosive devices were designed to minimize the dispersion of fission products.

Finally, confirmation of predicted hazards from fallout depends on the sensitivity and specificity of the analytical techniques and instrumentation available. Although radioiodine was a special case because of its concentration in a small organ, the measurements made on human subjects during the 1950s aroused no special concern. The MPC in water during that period was 30 nCi $L^{-1}$ (1.1 kBq $L^{-1}$) for continuous intake whereas fallout exposures were for only brief periods so no sustained thyroid burden would occur. A summary of improvements in measurement capability for radioiodine and other radionuclides appears in the next two sections.

## IV. THE MEASUREMENT OF RADIOACTIVE I IN THE THYROID GLAND

The term "bioassay," as used by health physicists, is any procedure for determining the amount of a material in a subject either by measuring the rate of intake and elimination of the material or its concentration in certain tissues as described below. For radioactive materials which emit photons, an effective procedure is whole-body counting, discussed in the next section. Because of its utility for the study of thyroid function, radioiodine became a chemical of choice for this purpose in the medical community.

In 1934 Fermi produced a radioiodine ($^{128}$I) and other radionuclides by neutron activation (Fe34). The half-life was very short, however, so most tracer studies were performed later in that decade when $^{130}$I became available (Ha38; Ha39; Ha42; He38; He42). In 1946, $^{131}$I which has an eight-day half-life was produced in quantity at Oak Ridge National Laboratories (Ch55). This is the most important radioactive isotope of I produced in nuclear weapons tests because of its yield. For many years, it was the isotope of choice for clinical uptake studies as well as for experimental research and is still used for radiotherapy of the hyperactive thyroid gland.

Many innovations in the design and placement of detectors and shielding for clinical thyroid studies were devised in order to improve sensitivity and geometry (Sk49; Br53; Ch55; Bu57). Berson and Yalow, in 1954 (Be55), used a Geiger-Mueller tube (Ge28) to study thyroidal $^{131}$I uptake in patients administered 15–20 nCi (0.56–1.74 MBq) as a tracer dose. Unfortunately, most of these early clinical papers do not describe counter efficiencies or other useful details such as calibration against certified standards. It should be noted that most of the methodology used in the detection and quantification of radioiodine in the thyroid gland from nuclear weapons tests was developed as a result of clinical diagnostic and therapeutic studies.

Scintillation counters using plastic and anthracene phosphors described in 1947 (Ka47)

* The Plowshare Program was established by the AEC in 1957 to promote peaceful uses of nuclear explosives, e.g. digging canals, dredging harbors, fracturing ore bodies, etc. (The name stems from the biblical passage in *Isaiah* on beating swords into plowshares.)

were used in clinical applications as early as 1951 (Ko51). Small thallium-activated sodium iodide detectors (NaI[Tl]) were first introduced in 1948 (Ho48) and became generally available in the early 1950s, however, at that time these were individually fabricated detectors used for research purposes only. Clinical uptake or thyroid function studies used 10–50 nCi (0.37–1.85 MBq) of $^{131}$I in a single dose. To reduce the tracer dose, Rall (Ra56) connected NaI detectors to pulse-height discriminators and calibrated with phantoms to correct for geometry. A tracer dose of 10 $\mu$Ci (0.37 MBq) was estimated to deliver about 15 rad (0.15 Gy) to the adult thyroid.

Gamma spectrometers, using sensitive (large-volume) NaI(Tl) crystals and multi-channel pulse-height analyzers, were not generally available before the test moratorium of 1958 and were not even available as semiportable field instruments, which could be used to monitor exposed persons, until the mid-1960s.

All the above relate to *in-vivo* counting of $^{131}$I in the thyroid gland. *In-vitro* counting is much more sensitive but can only be performed when thyroid glands have been surgically removed or obtained at autopsy. Counting geometry and efficiency were improved by dissolving tissue samples with sodium hydroxide or enzymes before counting (Pe52). In 1953 Van Middlesworth measured $^{131}$I in the excised thyroids of cattle and sheep collected from meat processors in the United States as a biological monitor for nuclear weapons tests in Nevada (Va54). Similar studies were discussed in Section III above.

In 1962, Eisenbud *et al.* (Ei62) stated that during the moratorium on testing, established in 1958, no new data on the behavior of radioiodine from weapons testing was forthcoming until resumption of testing by the Soviet Union in 1961. However, during the three-year moratorium, many advances were made in the capability of measuring the $^{131}$I in the environment and in humans. This came about as a result of the improvement in the general availability of $\gamma$ spectrometric equipment and large NaI crystals. Eisenbud used such a crystal and a multi-channel analyzer to achieve a minimum detectable amount of 23 pCi (0.8 Bq) in excised thyroid glands. The first *in-vivo* counts at this low level (Ei63) were made in a whole-body counter. The minimum detectable amount was approximately 18 pCi (0.67 Bq) of $^{131}$I for an "average child" and 20 pCi (0.74 Bq) for an "average adult" in this system.

Although there have been relatively few major developments in the detection methodology, instrumentation has been greatly improved with modern electronics along with advances in mass-produced cast shielding as opposed to the "home-made" detector systems shielded or collimated with Pb bricks. As a result, the detectable amount of $^{131}$I in the thyroid has been reduced from about 1 $\mu$Ci in the 1940s to a few picocuries at present.

A limited number of small lithium-drifted germanium (Ge[Li]) detectors became available during the mid to late 1960s that were useful for differentiating various fallout radioiodines in forage, milk and excised glands or tissues when long counting times were used (Po68). These would have been of little use for *in-vivo* counting of human populations where exposures were minimal. Over the past decade, the development of large ultra-pure Ge detectors with very high resolution may have reversed this situation. However, in recent years there has been no release of radioactivity from the NTS where this could be tested.

Finally, it should be pointed out that chronologically pinpointing the reported introduction of a new instrument or technology is not tantamount to its acceptance by the scientific or health monitoring community. Considerable time is usually required for technology transfer, refinement, commercial development, acceptance by the monitoring community, and adequate personnel training, if indeed the system lends itself to field use. In some instances this sequence of events may take five or more years before a reliable field monitoring system is deployed.

Two notable field studies to measure thyroidal radioiodine burdens in people exposed to NTS fallout in the mid-1960s should be mentioned here. These were carried out by the PHS, using semiportable counting systems, following the Palanquin event (PHS70) on 14 April 1965 and the Pin Stripe venting (EPA72) on 25 April 1966. After the Palanquin event, a Plowshare cratering test, 37 offsite residents from three sites—Paradise Valley (approximately 450 km NNW of the NTS), Willow Creek (97 km NNE of the NTS) and Clarks Station (105 km NNW of the NTS)—were brought into Las Vegas, NV, to be counted

in the whole-body counter. This counter consisted of an 80-ton shield and associated counting equipment mounted on two railroad cars. It used a 4″ × 11″ (10 × 28 cm) NaI(Tl) detector with a 400-channel analyzer. In this study it was assumed that all detectable radioiodines were in the thyroid gland. All subjects were counted between 25 April 1965 and 6 May 1965, or 11 to 22 days following the detonation. Two of the subjects, one at Clarks Station and one at Willow Creek, had estimated integrated exposures of 160 mrad (1.6 mGy) each. The former was an 11-yr-old child, while the latter was a one-month-old infant. A 15-yr-old at Clarks Station had an estimated dose of 105 mrad (1.05 mGy) and all others were below 75 mrad (0.75 mGy). Cumbersome systems such as this would be poorly suited to rapid deployment for the study of large population samples in emergency situations.

A portable "Mobile Thyroid Counting Trailer" was deployed by the PHS 50 hr after the Pin Stripe venting. This trailer was equipped with a 2″ × 5″ (5 × 13 cm) NaI(Tl) detector, a pulse-height analyzer, and appropriate shielding. The trailer was originally placed in an area of relatively high local background and the individuals measured had very low radioiodine burdens which necessitated removal of the trailer to an area with a lower background (Alamo, NV), until 30 April when it was moved to Ursine, NV. Of 78 individuals measured, 25 had no detectable thyroid burden. The highest doses reported were in two individuals from the Hiko/Alamo, NV, area (approximately 100 km from the NTS) who had estimated doses of between 150 mrad (1.5 mGy) and 300 mrad (3.0 mGy) to the thyroid from radioiodine. There were 14 individuals from this area with reported doses between 50 and 150 mrad (0.5–1.5 Gy) and 51 with reported doses less than 50 mrad (0.5 mGy). In the Pioche/Ursine/Panaca, NV, area (approximately 160 km from the NTS), 10 individuals who were measured had background levels of I in the thyroid and one other had a trace (<50 mrad or <0.5 mGy).

In recent years, the potential for exposure has been greatly reduced because of underground testing, and little attention has been paid to the development of sensitive "state-of-the-art" mobile systems for thyroidal radioiodine surveys in large population samples. Instead, reliance has been placed on improved environmental monitoring techniques to provide early warning of contamination so that protective actions can be taken.

## V. OTHER BIOASSAY DEVELOPMENT

Whole-body counting (a procedure for determining the radioactivity in an intact subject) began in the 1920s with the need to measure the body burden of $^{226}$Ra. In 1929, a procedure using an ionization chamber to measure as little as a 5-$\mu$g body burden was published (Sc29). Later, an ionization chamber was adapted to measure exhaled $^{222}$Rn to indirectly estimate Ra burden (Ev33). Development of whole-body counting techniques progressed steadily from that time using different detectors, such as Geiger-Mueller counting (Ev37; Co57) and NaI(Tl) scintillation counting (Ma53; Ma62), and the more sensitive methods of multiple high-pressure ion chambers (Si52; Ra64), liquid and plastic scintillation counters (An57; Bi58), and Na(Tl) $\gamma$ spectrometry (Mi56; Ru57). Toward the late 1960s, using newer solid-state detectors, e.g. Ge(Li) detectors with multi-channel analyzers and computer analysis of the spectra, it was possible to quantitatively detect a large number of radioisotopes at relatively low concentrations when the equipment was properly calibrated (Po71).

Bioassay by measurement of radioactive materials in excreta or tissue samples was a somewhat more difficult procedure than whole-body counting. The measurement of exhaled Rn to estimate Ra body burden is an early example (Ev33). All the Rn activity in the breath sample was assumed to be due to decay of Ra in the body, and assumptions were made about the fraction of Rn so produced which was then exhaled, and it was further assumed that this fraction was invariable. For urinalysis, particularly after exposure to mixed fission products, inorganic analysis techniques were necessary along with half-life determinations, perhaps including determination of the energy of the emitted radiation. These analyses were difficult and time-consuming. The development of $\alpha$ and $\gamma$ spectrometry in the 1950s eased the problem somewhat, especially for $\gamma$ emitters. However, lack of human metabolic data for many stable elemental species led to large errors in estimating body bur-

dens of radionuclides when based on analysis of excreta.

Bioassay using single radioisotopes began in the 1930s as discussed above. Such studies continued into the 1940s when the Manhattan Project activities generated great concern over certain reactor-produced isotopes, such as Pu, and reactor constituents, such as U (He75). Major emphasis, though, was placed on those isotopes which were normal body constituents or analogs thereof, and particularly those which concentrated in certain tissues. Uptake and retention of I by the thyroid was thoroughly investigated because of its use in diagnostic studies and in therapeutics, but the isotopes considered hazardous at that time were those with long half-lives such as $^{137}$Cs and $^{90}$Sr (Sm54). Most of the tracer studies using bioassay techniques were conducted on experimental animals; e.g. the study of excretion and retention of $^{137}$Cs in dairy cows in 1952 (UT52). An extensive annotated bibliography of Sr and Ca studies during this period was published in 1962 (Wa62). It wasn't until 1955, with the development of scintillation spectrometry that Cs was detected in laboratory subjects (Mi56). In attempting to locate the source of the Cs, air filters from the laboratory were analyzed. However, overriding activities of Ce, Zr-Nb, Rh-Ru and other fission products masked the Cs activity. The absence of the spectra from these isotopes in humans suggested that there was little retention of them and that Cs might be following the same pathways into man as was Sr (Mi56; ANL57). In 1956, the importance of excretion analysis vis-a-vis whole-body counting was illustrated by this statement (La56):

> Data for humans are available for only a few radionuclides, and some of that is fragmentary. The development of whole-body counters may facilitate collection of excretion and retention data. However, because of high capital costs and space requirements, poor detection of alpha and beta emitters, and non-differentiation of external vs. internal deposits, it is unlikely that whole-body counting will completely replace excretion analysis.

In the 1959 congressional hearings (Ha59), the evidence presented indicated few significant advances in bioassay:

> The effects of mixed fission products deposited in man are not well understood. Uncertainties are greater than a factor of 10. The essential biological information is available for only a few isotopes. Dose estimates are based on the most hazardous single isotope and predictions made as to the amount of gastrointestinal tract damage.

In 1958 at the University of Utah (Ma58), an attempt was made to measure fallout in people through the use of a liquid scintillation counter. A two-channel analysis of whole-body spectra (a high-energy band for $^{40}$K and a low-energy band for $^{137}$Cs), revealed that uptake of Cs had occurred and, unexpectedly, that there was little difference in body burden between residents of the Salt Lake City area [average 68 pCi g$^{-1}$ K (2.5 Bq g$^{-1}$ K)] and residents of southwestern Utah who lived closer to the NTS [average 59 pCi g$^{-1}$ K (2.2 Bq g$^{-1}$ K)] (Ma58).

Two reported instances in which urinalysis was used to estimate body or organ burdens of fission products were mentioned in Section III. These were analyses of urine samples from military personnel and PHS monitors for $^{131}$I and $^{90}$Sr in 1955, and of urine samples from Marshallese people for $^{131}$I, $^{140}$Ba, $^{45}$Ca, $^{103}$Ru, $^{90}$Sr, rare earths and fissile material in 1954. These were tedious, time-consuming procedures but, except for I and Sr, could only lead to rough estimates of body burden because of lack of appropriate metabolic data (Sc58; Co80).

The Federal Radiation Council (FRC) expressed its concern about the lack of metabolic data in its first report in May 1960 (FRC60). However, by the time of the 1964 International Conference on Assessment of Radioactivity in Man (Do64; Ja64a), some advances had been made. The excretion rate observed in contaminated subjects was compared with the reference data obtained from subjects in which the level of contamination was known and had been systematically studied. These reference data, however, were still very scanty (Do64).

To summarize, bioassay has long been regarded as an important technique for measuring uptake and retention of radioactive materials in tracer or metabolism studies, usually carried out in the intact animal. In the early years, such studies were hampered by the sensitivity and limited analytical techniques available. As the sensitivity and specificity of the methodologies improved, more reliably quantitative results were achieved. During the early 1960s, large-volume scintillation

detectors and multi-channel analyzers were the significant developments which permitted rapid analysis of $\gamma$-ray emitters. These instruments proved to be generally adequate when tissue samples or samples of metabolic products contained only a few radionuclides. However, the spectra resulting from analyses of samples containing many $\gamma$-ray emitters, such as mixed fission and activation products found in fallout and nuclear debris, were far too complex for quantitative analysis. Thus metabolism or distribution studies using actual nuclear debris led to very imprecise estimates of both uptake and retention. More recently the development of very high-resolution solid-state Ge(Li) detectors, along with highly sophisticated multi-channel analyzers, computer systems and associated software, have made it possible to follow more than a dozen $\gamma$-ray-emitting radionuclides simultaneously in a single debris feeding study (Po71).

## VI. EXPOSURE STANDARDS FOR THE NTS

All the standards and guides mentioned in Section II were based on continuous exposure from normal peacetime operations except the guide for $^{131}I$ (FRC64). Before 1954 when *NBS Handbook* 59 was issued (NCRP54), no differentiation between occupational and population exposure was made in the standards. At that time, it was recommended that the exposure of persons under age 18 be limited to one-tenth the permissible occupational exposure. This had the effect of limiting the exposure of the whole population to a value well below that considered acceptable for radiation workers. In the 1958 addendum to *NBS Handbook* 59 (NCRP58), it was specifically recommended that all exposures to the general population be limited to one-tenth that of occupational exposure standards.

For operations other than those for which the standards were set, such as nuclear weapons tests, the guidelines were based on the principle that any exposures above the maximum permissible dose should be justified by the benefits derived from the event that caused the exposure. Nuclear weapons tests were considered to have an obvious benefit, namely national security, against which additional exposure of the population to radiation could be balanced (Jo57; St57; NAS72). In fact, some workers even speculated that radiation might have some evolutionary benefits (Jo57). However, the AEC was relatively conservative in setting safety guidelines since it set 3 R (0.8 mC $kg^{-1}$) in 10 weeks as the maximum external exposure off-site for the 1952 test series (AEC53a).

Normally, the tests in the early 1950s did not extend beyond three months per year and, in most cases, the maximum fallout exposure from separate tests did not occur in the same geographical area, so few, if any, population exposures exceeded 3 R $yr^{-1}$ (0.8 mC $kg^{-1}$) (AEC58).

This 3-R maximum external exposure guideline was published in the 1953 book *Continental Weapons Tests—Public Safety* (AEC53b). Along with the external exposure guide, there were also stated guides for air and drinking water. These guides were: in air, 1 $\mu$Ci $m^{-3}$ (37 kBq $m^{-3}$) averaged over 24 hr for particles less than 5 $\mu$m in diameter and, for water, 5 $\mu$Ci $L^{-1}$ (185 kBq $L^{-1}$) measured three days after the test. These levels were not expected to cause internal exposures exceeding the external exposure guide. Similar guides for air concentration and external exposure had been established for the 1951 Buster-Jangle test series by the Jangle Feasibility Committee (Sh53). At that time, no guide was set for drinking water because most potable water was not considered to be exposed to fallout.

For the 1955 tests, the external exposure guide was changed to 3.9 R (1 mC $kg^{-1}$) over a period of 1 yr to the off-site population (AEC55). This was about one-fourth the extant permissible occupational exposure (NCRP54). There were no specific radionuclide concentration guides, but it was stated that at any location where the open-field $\gamma$ infinity dose exceeded 10 R (2.6 mC $kg^{-1}$) adequate sampling of water, air and foodstuffs was required to ascertain the conditions of possible contamination. Also stated were protective action criteria for evacuation of people, for remaining indoors, for decontamination of vehicles and personnel, etc. A revision of this publication in 1957 contained essentially the same guidance except that the 3.9 R (1 mC $kg^{-1}$) external exposure guide was referred to any exposure resulting from Operation Plumbbob. These criteria were extended to Operation Hardtack in 1958 (AEC58).

After the test moratorium which ended in 1961, the AEC revised the off-site exposure guides somewhat (PHS64). The 3.9 R (1 mC $kg^{-1}$) per test series for external exposure was further qual-

ified so that no one would receive more than 10 R (2.6 mC $kg^{-1}$) in 10 yr. In addition, the concentration guides for air and water were restricted to one-tenth the continuous occupational exposure levels stated in *NBS Handbook* 69 (NCRP59). These guides remained in effect until 1977 when the external exposure guide was lowered to 0.5 rem $yr^{-1}$ (5 mSv $y^{-1}$) to an individual or 0.17 rem (1.7 mSv $y^{-1}$) to a suitable sample of the population, and the permissible air and water concentrations were reduced to one-thirtieth of the *NBS Handbook* 69 values for continuous occupational exposure (ERDA77).

## VII. DISCUSSION

This selective survey of published material on the evolution of exposure standards applicable to activities conducted at the NTS indicates the development of increasing conservatism in the standards based principally on judgmental decisions because little, if any, data were available on the effects of low-level, continuous exposure from external or internal radioactivity. Although internal dosimetry was a well-developed discipline by the time of the first weapons test (Trinity in 1945), there were few useful data available, except for some selected radionuclides used in diagnosis and therapy. Most available data, derived from animal experiments, were concerned with normal body constituents or their analogs and as such were not directly applicable to mixed fission-product exposure.

Since the early tracer experiments were usually single-element studies, the radioactivity of analyzed tissues or excreta could be ascribed to the administered isotope. When, however, exposure to a variety of radioisotopes occurred simultaneously, analysis of samples required long and tedious radiochemical procedures because the detectors used until the late 1940s consisted mainly of ionization chambers, proportional counters, and Geiger-Mueller counters which do not provide a means for differentiating among isotopes. The availability of ZnS as an $\alpha$-scintillating material, first described in 1903 (Gl58), led to an intensive search during the 1940s and 1950s for similar materials for $\beta$ and $\gamma$ emitters to increase the sensitivity and selectivity of detection (Si65).

Examples of these are the crystalline scintillators such as anthracene, various commercial plastics, and the alkali halides such as NaI(Tl) (Au67). The limitations associated with bioassay and measurement during this time did not relieve the paucity in experimental data for many radionuclides, so responsible scientists in the field judgmentally evaluated the radioisotopes produced by fission and selected $^{90}Sr$ to be the most hazardous (see Section II) (Sm54).

Significant exposures from many of the other radioisotopes produced by fission reactions were not considered likely at that time because several factors were assumed to be relevant. These included: (1) a short half-life so the radiation would not persist long enough to deliver a harmful dose; (2) the lack of similarity to normal body constituents so that retention would be very small; (3) if passed through the metabolic processes of the human food chain, decay and insignificant retention would appreciably diminish any potential hazard; (4) that surface deposition on food crops would not result in firm bonding so normal food preparation would be expected to remove most of the deposited radionuclides; and (5) that windborne fallout clouds at distances far from the NTS would not maintain atmospheric concentrations long enough for inhalation to be a significant route of exposure. Therefore, the emphasis was placed on minimizing the external exposure of the off-site population.

The considerations outlined in the preceding paragraph appeared to be confirmed by actual experience gained as a result of the early nuclear weapons tests. For example, in the 1953 tests, in a location where the survey-meter reading was 1.63 R $hr^{-1}$ (0.4 mC $kg^{-1}$ h) the external dose would have been 72 R (18 mC $kg^{-1}$) for the year, many times the permissible level (Ra54), yet the 24-hr air concentration of 1.1 $\mu$Ci $m^{-3}$ (40.7 kBq $m^{-3}$) was near the permissible concentration. Other evidence suggesting that external exposure was the limiting factor is listed in Section III, items (b) and (c).

Furthermore, a bioassay study was conducted in 1955 (Operation Teapot) in which 24-hr urine samples were collected and analyzed for $^{90}Sr$ and $^{131}I$ as discussed in Section III. The results suggested that no significant internal exposure had occurred to off-site populations. Even radioiodine itself had not been ignored during this time. In addition to urinalysis studies, studies of human and cattle thyroids were undertaken. References

Gu54, Sc58 and Wh58 represent some of these studies. The most dramatic study involved the Marshall Islanders whose accidental exposure following a weapons test provided direct evidence of the importance of external exposure relative to internal exposure, at least as based on the early calculations of dose (Co80). After thyroid changes appeared in Marshallese children, a calculation published in 1964 (Ja64b) suggested that significant thyroid exposures may have occurred in the children living in the area.

Because of the theoretical considerations and experimental data available on the importance of external exposure and because of the difficult analytical problems and imprecision in available bioassay methodology, the emphasis in off-site radiological safety monitoring was placed on minimizing external exposure. Internal exposure was not neglected, however, because assays of tissues and food items for $^{90}Sr$ were widespread in the early 1950s. Furthermore, as the methodology improved, and even before it became generally available, samples were submitted for isotopic analysis. An example is the isotopic analysis of milk samples which began in early 1957 by the PHS (PHS60).

As the exposure standards were progressively lowered during the 1950s and 1960s, it was recognized that a few people in the area surrounding the NTS may have had single exposures exceeding the more modern standards. It should be emphasized, however, that these "over-exposures" if they did indeed occur, were of relatively brief duration (i.e. a matter of days or weeks): not continuous exposures as is the basic consideration in setting the standards (AEC58). Furthermore, it should be recognized that the standards were lowered not because of any evidence of harm caused by exposure at the early higher permissible levels, but because of judgment by groups of experts that operations could be conducted with lower exposure guidelines without undue difficulty (Ta73).

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